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Flux and spectrum dynamics of relativistic solar protons in the event of 29 September 1989. New computational modeling by the ground level data

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Abstract. Using a technique of computational modeling, the parameters of spectrum, pitch-angle distribution and anisotropy of relativistic solar protons (RSP) for 17 moments of time in the event of 29 September 1989 have been obtained. It allowed to construct the intensity profiles in different ranges of energy and to study the energetic spectrum dynamics in detail. The event has been shown to comprise the early, rigid impulse-like intensity increase (prompt component, PC) and late gradual increase with a soft spectrum (delayed component, DC). The spectrum of prompt component was exponential in rigidity and softened with time. The DC spectrum had a variable slope which did not change during almost an hour in the late phase of event. Based on those results, we suggest a combined model of generation of two RSP components in a system "reconnecting current sheet - coronal mass ejection (CME)". The PC particles are proposed to be accelerated by electric field arising in the reconnection process in a tailing part of ascending CME. The DC particles are probably due to the acceleration by plasma turbulence in the flare or by a CME-driven shock wave.

1 Introduction

Large solar event of 29 September 1989 has been extensively studied during past 10 years, and at present more than 200 appropriate publications are available (as a review see Miroshnichenko et al. (2000)). In particular, it was shown (Vashenyuk at al., 1997; Vashenyuk and Miroshnichenko, 1998) that a number of the peculiarities observed in the event can be explained by two-fold ejection of relativistic protons from the Sun. Just at the early stage of this event very hard particles have been ejected with a strong anisotropy outward the Sun. At the second ejection that occurred about 1 hour later the spectrum of RSP has become softer, and a bi-directional anisotropy was found (Vashenyuk at al., 1997; Vashenyuk and Miroshnichenko, 1998; Vashenyuk and Pchelkin, 1998) to exist in this latter case. By the methods of a computational modeling the event of 29 September 1989 has been analyzed by several research groups (Dvornikov and Sdobnov, 1997; Lovell et al., 1998; Vashenyuk and Pchelkin, 1998). Those researchers have estimated the parameters of primary flux of solar protons for three (Lovell et al., 1998; Vashenyuk and Pchelkin, 1998) and four (Dvornikov and Sdobnov, 1997) moments of time. In the present paper the modeling has been accomplished for 17 moments of time, that allowed us to trace the flux dynamics of RSP in more detail.

2 Modeling technique

Modeling procedure of the event of 29 September 1989 by the Earth's surface data included the normalization of data to a standard barometrical pressure (1000 mb) was carried out by the two attenuation length metod (Mc Cracken, 1962; Kaminer, 1968). The attenuation lengths due to solar protons were taken from (Ahluwalia and Xue, 1993). Determination of asymptotic viewing cones of the 42 NM stations under study based on the particle trajectory calculation in the model of geomagnetic field by Tsyganenko-89 (Tsyganenko, 1989). A trajectory was traced up to the boundary of the magnetosphere. The direction opposite to the NM viewing direction corresponds to the asymptotic direction of particle approach at given rigidity. Then the responses of all the 42 neutron monitors have been computed. Details of these computations are in (Pchelkin and Vashenyuk, 2001). By these computations the following forms of rigidity spectrum and pitch-angle distribution were used. $J_{\parallel}(R) = J_O R^{-\gamma}$ is a rigidity spectrum of RSP flux in the direction of anisotropy axis. γ monotonically increases in rigidity and $\Delta\gamma$ is an increase per 1 GV(Cramp et al, 1993), $F(\theta(R\ )) \sim exp(-\theta^2/C)$ is a pitch-angle distribution (PAD) of primary protons in the IMF (Shea and Smart, 1982), $\theta(R)$ defines an angle between the direction of maximum intensity of particles and asymptotic direction of approach at

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Table 1. Modeled parameters of relativistic solar protons.

UT	11:52	12:07	12:17	12:37	12:52	13:07	13:17	13:27	13:37	13:47	14:07	14:17	14:32	14:47	15:07	15:17	15:37
J_0	0.49	1.08	2.2	5.8	8.2	31.5	33.3	62.2	74.9	102.5	124.1	129.6	133.2	122.2	132.0	128.0	122.0
Υ	1.00	0.90	1.08	1.64	1.81	2.97	3.02	3.5	3.70	4.06	4.31	4.36	4.44	4.44	4.53	4.58	4.64
$\Delta\Upsilon$	0.12	0.11	0.14	0.16	0.19	0.13	0.13	0.12	0.11	0.08	0.09	0.11	0.12	0.12	0.14	0.14	0.16
C	1.60	2.99	3.64	5.09	6.32	7.55	9.32	8.75	9.47	9.47	11.02	11.43	11.69	11.78	10.38	10.69	10.81
θ , °	63	70	68	75	81	84	89	81	75	72	84	87	84	86	97	100	108
φ , °	277	254	258	255	254	249	252	261	258	257	258	260	265	267	273	275	283
ε , %	12.53	3.70	2.97	2.94	2.98	2.64	2.10	1.68	1.61	1.19	0.78	0.88	1.00	0.91	1.23	1.38	1.20

a given rigidity. Unknown parameters of solar proton flux are six quantities: normalisation constant of the spectrum J_O, direction of the anisotropy axis (GSE coordinates, θ and Φ), two constants in the relations for the rigidity spectrum, γ and Δγ, and a constant of pitch-angle distribution $C=2\sigma^2$. These parameters are determined with the optimization methods (Dennis and Schnabel, 1983) by resolving a system of constrained equations. Then, we solved, in essence, a nonlinear least-square problem that was reduced to search a minimum of the function *SN* at the optimal set of parameters:

$$SN = \sum_j ((\Delta N/N)_{j\,\mathrm{calc}} - (\Delta N/N)_{j\,\mathrm{observ}})^2 \rightarrow \min \qquad (1)$$

Inscriptions in the indexes in the relation (1) correspond to calculated and observed amplitudes of GLE at the j-th cosmic ray station.

3 The results of modeling

The combinations of mentioned parameters of RSP have been obtained for the 17 moments of time between 12:00 and 16:00 UT. In Table 1 we summarize the results of determination of RSP parameters at the 17 selected moments of time. The quantity ε is a residual error.

Figure 1 shows intensity-time profiles at four neutron monitors (Hobart, Apatity, Irkutsk and Inuvik) derived by

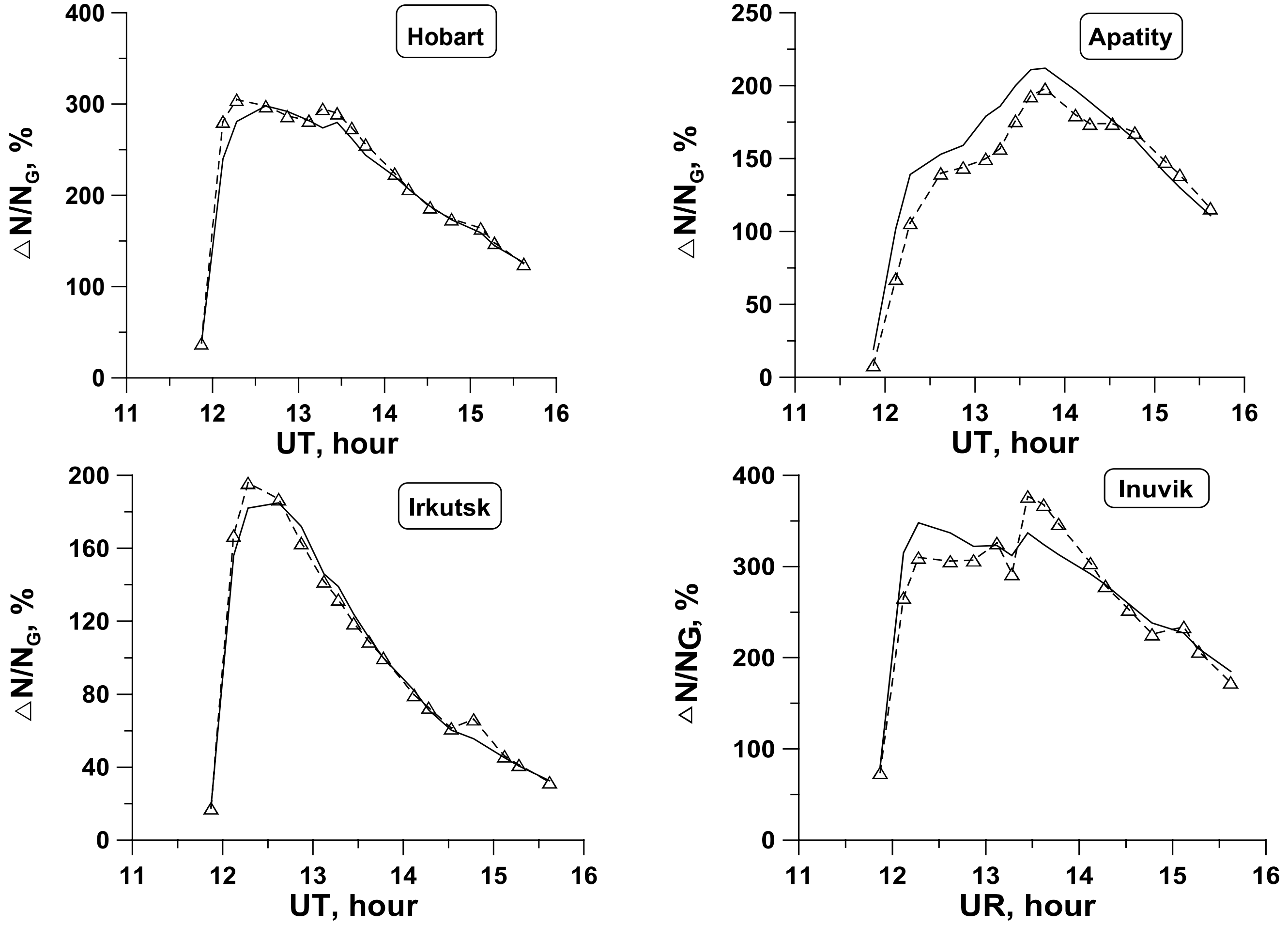

Fig.1. Modeled (solid lines) and observed (triangles) intensity-time profiles of ground-level increases on 29 September 1989 at a number of neutron monitor stations.

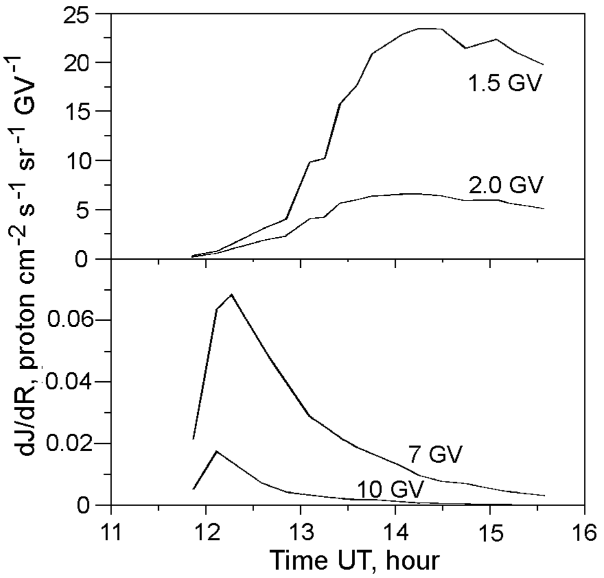

Fig.2. Derived differential intensity-time profiles of solar protons for different rigidities outside the Eart's magnetosphere.

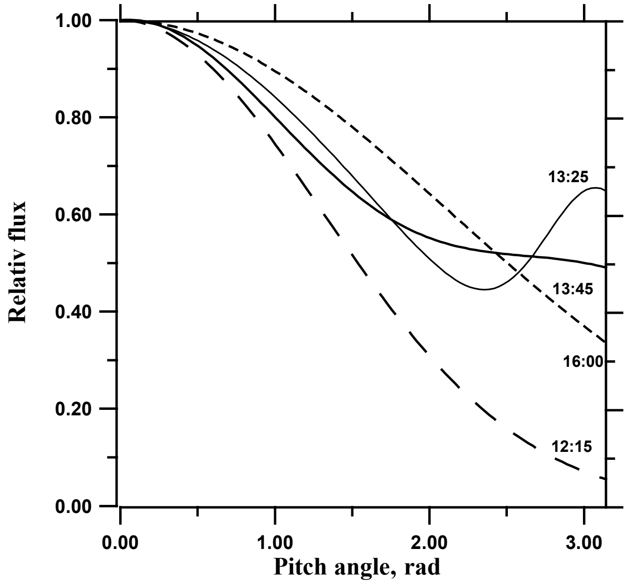

Fig.3. Derived solar proton pitch-anfle distributions in the different moments of time of the 29 September 1989 GLE.

the results of modeling at the 17 subsequent moments of time (solid lines). Real (observed) values of intensity are shown by triangles. In total, in this way we reconstructed 42 profiles (according to a number of neutron monitors involved). The character of visible discrepancies is typical for such kind of modeling.

Time profiles of differential intensity at RSP rigidities of 1.5, 2, 7 and 10 GV are given in Figure 2. It is seen that at high rigidity, only one peak of RSP intensity was observed early in the event. At lower rigidities an increase starts some later and corresponds to the second ejection of relativistic protons in this event (Vashenyuk et al., 1997; Vashenyuk and Miroshnichenko, 1998).

Figure 3 shows the pitch-angle distributions of RSP during the early phase of event as well as during the second maximum and late phase. It is seen that the prompt RSP component has pitch-angle distribution more narrow than at late phase. And during the second maximum of GLE the PAD becomes bidirectional what may be related with possible loopelike IMF structure and injection solar particles into the both ends of the loop rooted on the Sun (Vashenyuk et al., 1997). The similar modelled PAD were obtained also by Lovell et al.,(1998).

Figure 4a shows the energy spectra of RSP, obtained for several subsequent moments of time. Thin lines mark the spectra observed after the first ejection from the Sun, solid line at 13:47 UT corresponds to the spectrum related to the second peak.

For the four moments of time after the first ejection we have constructed also the rigidity spectra of RSP (Figure 4b). These spectra display an exponential dependence on rigidity, this feature being characteristic for particle acceleration by DC electric fields (e.g. Dorman and Miroshnichenko (1968)). At the same time, the spectrum slope is seen to increase in time. It should be noted that the spectrum of second ejection did not undergo considerable changes within the time interval 13:17 - 14:07 UT.

4 Discussion

Our modeling results clearly demonstrate two components of RSP, prompt and delayed ones (Vashenyuk et al., 1997; Vashenyuk and Miroshnichenko, 1998), that, supposedly,

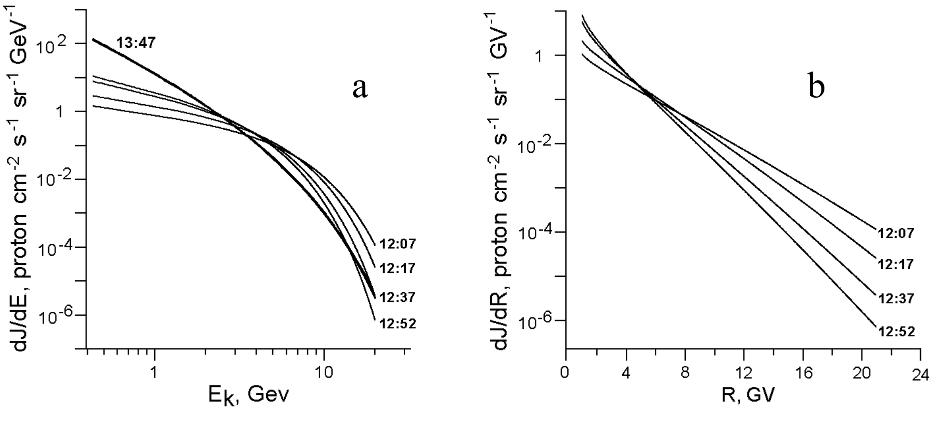

Fig.4a. Derived energy spectra of relativistic solar protons outside the Earth's magnetosphere at different moments of time on 29 September 1989, for the first and second intensity peaks (thin and thick lines, respectively).

Fig.4b. Dynamics of rigidity spectra during the first intensity increase in the GLE of 29 September 1989. Note an exponential form of the spectrum and its softening with time.

have been accelerated on 29 September 1989 at coronal heights (Vashenyuk et al., 2000). Subsequently, they have been released from the Sun with a shift in time. Possible mechanism of generation of prompt component may be an acceleration of particle in DC (disruption current) electric field arising in the process of reconnection of opposite magnetic fields high in the corona (Perez-Peraza et al., 1992). As to the delayed component, a corresponding mechanism of RSP generation in the event under study may be a stochastic acceleration by plasma turbulence in the flare volume or its vicinity (Miroshnichenko et al., 1996). On the other hand, Lovell et al. (1998) advocated a shock wave acceleration as a generation mechanism of solar cosmic rays in the 29.09.1989 event.

A model of RSP generation providing with two mechanisms of acceleration and release of accelerated particles into interplanetary space may be related to a configuration of a coronal mass ejection (CME) that appears at the separation surface of magnetic polarities in the solar corona (Kahler, 1996). Then, the generation of PC particles is due to the acceleration in DC electric fields arising in the process of reconnection of opposite magnetic fields in the trailing part of the CME (Litvinenko and Somov, 1995). Exponential form of the rigidity spectrum for the prompt component of RSP (Figure 4b) gives an evidence of particle acceleration by DC electric field (Dorman and Miroshnichenko, 1968). The regular softeness of the prompt component spectrum with time may be due to shift of the reconnecting layer higher in the corona where magnetic field strength (main factor influencing the RSP spectrum rigidity (Perez-Peraza et al., 1992) is weaker.

Particles of the delayed component (DC), originally being trapped in magnetic arches in the lower corona, supposedly are accelerated by stochastic mechanism in the process of interactions with MHD turbulence in expanding flare plasma (Miroshnichenko et al., 1996). This accelerated in the low corona population of particles may be carried out to the upper corona by arising CME and injected then into interplanetary space. The invariability of the delayed component spectrum in course of more then two hours since 13:47 (Fig. 4a) speaks for this mechanism.

The questions of modeling of the RSP spectra in the sources that have given rise to the event of 29 September 1989 are discussed in a separate paper (Vashenyuk et al., 2000). In the same paper the estimates of source parameters for the prompt component are given. As a whole, however, after 10 years of intensive study of the event no generally accepted acceleration scenario exists (Miroshnichenko et al., 2000). Apparently, detailed modeling efforts will be still required to construct a comprehensive picture of this historic event.

5 Summary

The responses of 42 neutron monitors of the worlwide network during the GLE have been computed. By methods of mathematical optimization by comparison of these responses with observations on 42 neutron monitors the parameters of relativistic solar proton spectra, anisotropy and pitch-angle distribution in interplanetary space for 17 moments of time have been obtained. It is shown existence of two distinct particle populations, the prompt and delayed one in the flux of relativistic solar protons. The prompt component was remarkable by the relatively short duration, rigid spectrum, and narrow pitch angle distribution. The delayed component has appeared ~1 hour later and had a gradual intensity profile, softer spectrum and a wide pitch angle distribution, possible related with a bidirectional anisotropy.

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